In a scenario that portrays actual practice more accurately, the multinomial distribution is the better representation of the number of active up-links. The multinomial distribution accommodates non-uniform statistics throughout the various LMDS cells, allowing analysis for any specified level of clustering. This is useful for representing, for example, a Teledesic cell consisting of dense urban use, moderate suburban use, and infrequent remote use.

Consider an example where there are three active LMDS cells within a Teledesic cell. The three cells have an average active TST usage of p1N, p2N, and p3N, respectively. The weighting function for computing system-wide availability is p1, p2, and p3, respectively, for the three active cells, and zero for all remaining cells. The cell with the highest FSS activity experiences the worst LMDS availability; in addition, that same cell has the largest weighting factor applied to the system wide availability calculation. As it should be, the areas of greatest usage (greatest number of users affected) make the greatest contribution to the availability computation.

In contrast, the Bellcore report averages the availability of 4 clustered cells each with a weight of 1/64, with the remaining 60 (100 percent availability) cells also receiving a weighting of 1/64 each.

3.5 CRITIQUE OF BELLCORE AVAILABILITY ANALYSES

Figure 3-4 in the Bellcore report presents the results of their analysis of the degradation of the CellularVision hub-to-subscriber link due to interference from 15 Teledesic standard terminals (TST) in a Teledesic cell transmitting at a T1 rate. We note that even when the interference is averaged over 64 LMDS cells, the LMDS availability does not quite achieve the objective of 99.9 percent for a required C/(N+I) of 13 dB. Since a maximum of 39, rather than 64, CellularVision cells could occupy the area of a Teledesic cell, the LMDS system-wide availability would be less than the value of 99.84 percent taken from Figure 3-4 in the Bellcore report.

A more significant measure of performance however, is the availability of acceptable LMDS service in the affected cells, where FSS transmitters are likely to be clustered (the curves included in Figure 3-4 for performance in clustered cells portray this information). Availability when all 15 Teledesic transmitters are clustered within 8 LMDS cells is degraded to about 99 percent at the same 13 dB C/(N+I) ratio. It is degraded further (to about 98 percent) for a four-cell cluster and to about 95 percent for a two-cell cluster.

Figure 3-8 in the Bellcore report presents the results of their analysis of the degradation of the CellularVision and Texas Instruments (TI) hub-to-subscriber links due to interference from 1440 Teledesic standard terminals in a Teledesic cell transmitting at 16 kbps. Bellcore based this analysis on a uniform distribution of TSTs throughout the 53-km-square area encompassed within a Teledesic cell. The computed availability for CellularVision and TI

LMDS is 99.65 percent and 99.7 percent respectively at the 13-dB C/(N+I) level; as in the case of T1 rate interferers, this fails to meet the design objective of 99.9 percent availability.

Use of uniformly distributed interferers in the analysis of availability in the presence of 16 kbps transmitters is a serious shortcoming in the Bellcore analysis because it neglects the clustered distribution of TSTs that will inevitably result from concentration of businesses and residences within the overall area. Given more time, MITRE would have performed simulations to determine the effects of clustering. In lieu of performing independent simulations, we have reviewed the results of simulations performed by the LinCom Corporation and by NASA Lewis Research Center (LeRC)[1].

The availability computed by NASA (99.70 percent) compares closely to the Bellcore value of 99.65 percent when uniform distribution of transmitters in a 53-km-square area and the modified LMDS system parameters used by Bellcore are considered. When the 1,440 FSS terminals are clustered, the NASA simulation produced LMDS availability in clear air of 99.3 percent, 98.48 percent, 96.64 percent, and 93.83 percent for 16, eight, four, and two LMDS cells, respectively. The results depart significantly from the 99.9 percent availability objective for LMDS.

LinCom also simulated 1,440 uniformly distributed TSTs in a Teledesic cell, computing availability based on the peak interference spectral density rather than total interference power (because the Bellcore report states that this assumption was used in their calculations). LinCom found an LMDS availability of 80.64 percent in clear sky and 9.58 percent in rain, for an average availability of 79.93 percent. It is obvious that Bellcore did not perform their calculations based on peak interference spectral density but on total interference power, as did NASA and the NRMC (see Section 6.1, page 49, of the NRMC Final Report).

The Bellcore report does not analyze, in detail, the interference into an LMDS receiver from Spaceway terminals. The report incorrectly states that one Spaceway spot beam has a capacity for 60 T1 simultaneous uplinks, and then uses this value to calculate a density of one active uplink every 5530 square km. This implies the assumption that the Spaceway terminals are uniformly spaced within the spot beam.

In reality, each Spaceway satellite uses dual polarization, and has a capacity in each spot beam of 120 simultaneous T1 uplinks. And since two Spaceway satellites will serve each spot beam area in North America re-using the same 500-MHz frequency band that is shared with LMDS (from orbit positions separated by 2 degrees), the actual number of simultaneously active T1 terminals that can be supported in a single Spaceway spot beam is not 60 but 240. These factors make it clear that there can be as many as 240 active Spaceway T1 terminals or 960 384-kbps terminals (or more likely, some mix of the two types of

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1 We understand that the results of NASA's simulations will be filed with the FCC by NASA and that the results of the LinCom simulations will be filed with the Commision.

terminals) clustered in a few LMDS cells. If Spaceway were to share the same 1000 MHz of spectrum with LMDS subscribers, there would be as many as twice this number of Spaceway terminals clustered in a small number of LMDS cells (that is, up to 480 active Spaceway T1 terminals or 1,920 active 384-kbps terminals).

It is plausible to expect that one-third of the terminals in the spot beam that includes Washington, DC, for example, could be clustered in the Washington metropolitan area of roughly 50 km by 40 km, or about seven tenths of the 53-km-square area of a Teledesic cell. Calculations made by the NRMC concluded that Spaceway T1 terminals would interfere with LMDS subscribers at somewhat greater distances than would Teledesic T1 terminals. The 50-km by 40-km Washington metropolitan area could accommodate 27 CellularVision cells.

Looking at the four-cell cluster curve (corresponding to an average of about four FSS terminals per LMDS cell) in Figure 3-4 of the Bellcore report provides insight into LMDS availability in the Washington metropolitan area when 80 Spaceway T1 terminals are transmitting (40 to each satellite in the 500-MHz frequency band that is shared with LMDS and having an overlap between LMDS and Spaceway frequencies). Eighty Spaceway T1 terminals in 27 CellularVision cells averages four T1 terminals per LMDS cell, resulting in CellularVision degradation on the order of 2 percent, well above the desired 0.1 percent, even on average. Of course, some LMDS cells will have even greater degradation because of non-uniform clustering of FSS terminals. If Spaceway were to share entire 1000 MHz of spectrum with LMDS subscribers, the degradation would exceed 5 percent.

The Bellcore report does not address availability on the subscriber-to-hub link in the presence of interference from FSS terminals. This link is an integral part of proposals for establishment of an LMDS service—indeed, the subscriber-to-hub link is the feature that distinguishes LMDS from a broadcast program distribution service.

The Bellcore availability calculations used LMDS system parameters that vary significantly from the LMDS requirements provided to the NRMC. For example, Bellcore made three major changes to the CellularVision system design: they doubled the number of transmitters required by each hub and increased the power of each, they improved the sidelobe pattern of the subscriber antenna, and the design objective for C/(N+I) was dropped to 13 dB (from 26 dB).

We conclude that the Bellcore analysis of LMDS availability, even with the modified LMDS system parameters, fails to demonstrate the compatibility of LMDS and FSS in a common frequency band. Several key factors led to our conclusion:

> The system cannot achieve the objective C/(N+I) of 13 dB for a system-wide availability of 99.9 percent in the presence of the 15 Teledesic T1 terminals in a Teledesic cell assumed by Bellcore, even using the modified LMDS system parameters

The assumption that FSS terminal distribution will be uniform throughout the FSS beam area is unrealistic

LMDS availability in the presence of clustered Teledesic terminals (either T1 or 16 kbps) is not 99.9 percent but drops to the range of 99 percent to 94 percent

LMDS availability in the presence of clustered Spaceway T1 terminals is not 99.9 percent but is on the order of 98 percent or less

FSS networks in addition to Teledesic or Spaceway were not considered but would further degrade LMDS availability

The Bellcore report does not address the availability of the subscriber-to-hub link, even though the NRMC concluded and we show, that it represents a serious interference problem (Section 3.7 includes a quantitative discussion of this problem)

3.6. AVAILABILITY BASED ON ITU-R RECOMMENDED ANTENNA PATTERN

There is reason to question whether a consumer product antenna can be consistently produced and maintained in such a way that it performs better than the standard contained in the relevant ITU-R Recommendation which experts consider reflects the performance that can be expected. It is informative, therefore, to examine the effect on Bellcore's availability calculations of substituting the ITU-recommended pattern for the pattern used by Bellcore.

In cases where the ratio between the antenna diameter and the wavelength is less than 100, ITU-R Recommendation 699-2 recommends that the following equation be used:

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3} (\frac{D}{\lambda}\varphi)^2 \qquad \text{for } 0 < \varphi < \varphi_m$$

$$G(\varphi) = G_1 \qquad \text{for } \varphi_m \leq \varphi < 100 \frac{\lambda}{D}$$

$$G(\varphi) = 52 - 10 \log \frac{D}{\lambda} - 25 \log \varphi \qquad \text{for } 100 \frac{\lambda}{D} \leq \varphi < 48^\circ$$

$$G(\varphi) = 10 - 10 \log \frac{D}{\lambda} \qquad \text{for } 48^\circ \leq \varphi \leq 180^\circ$$

where:

$G(\varphi)$: gain relative to an isotropic antenna

φ: off - axis angle

D: antenna diameter

λ: wavelength

(φ, D and λ) expressed in the same units

G_1: gain of the first side - lobe $= 2 + 15 \log \frac{D}{\lambda}$

$$\varphi_m = \frac{20\lambda}{D}\sqrt{G_{MAX} - G_1} \qquad \text{(degrees)}$$

Table 1 shows the pattern used in the Bellcore analysis (this table is designated Table A-3 in the Bellcore report).

Table 1. Revised CellularVision Subscriber Antenna

Azimuth Angle (ø) from Boresight	**Mask (dB relative to boresight gain)**
0 to 7.2 degrees	$-3(ø/2.5)^2$
7.2 to 12 degrees	-25.0
12 to 60 degrees	-4-20 log ø
60 to 180 degrees	-40

The gain used in the Bellcore calculations for the CellularVision subscriber antenna in the first sidelobe is 6 dBi, compared to the 19.6 dBi yielded by the Rec. 699-2 pattern. The difference is 13.4 dB, meaning that the required separation distance would be 4.7 times greater than that calculated by Bellcore.

The gain used in the Bellcore calculations for the CellularVision subscriber antenna in the far sidelobes is -9 dBi, compared to the gain of -1.6 dBi derived from Rec. 699-2. In this case, the difference in gain is 7.4 dB, resulting in a required separation distance 2.3 times greater than that calculated by Bellcore.

We calculated the minimum required separation distance between a Teledesic T1 terminal and a CellularVision subscriber for various off-axis angles. We used the modified LMDS parameters suggested by Bellcore, including a criteria of 13 dB for C/(N+I), except for the subscriber antenna pattern, where we substituted the pattern for fixed-service antennas in Rec. 699-2. The first case is when the interferer is in line with the subscriber main beam:

LMDS carrier = 10.8 dBW - 135.5 dB + 31 dBi

= -93.7 dBW (from Bellcore's Table 1-1)

LMDS noise level = -125.4 dBW

N+I = -106.7 dBW for a C/(N+I) of 13 dB

C/I = 13.06 dB

G_t = -2.2 dBi

P_t = 0.85 dBW

G_r = 31 dBi

$G_r\lambda^2/4\pi$ = -19.55 dB(m^2)

Bandwidth correction

= 26.5 MHz/20 MHz

= 1.33

= 1.22 dB

$$10(\log 1/4\pi d^2) = - G_t - P_t - G_r\lambda^2/4\pi - 106.76 + 1.22$$

$$= 2.2 - 0.85 + 19.55 - 106.76 + 1.22$$

$$= -84.64 \text{ dB}$$

$$d = 4813 \text{ m}$$

The next case is when the interferer is in the first sidelobe of subscriber antenna axis:

$$G_r = 19.6 \text{ dBi}$$

$$G_r\lambda^2/4\pi = -30.95 \text{ dB(m}^2)$$

all other values are unchanged

$$10(\log 1/4\pi d^2) = - G_t - P_t - G_r\lambda^2/4\pi - 106.76 + 1.22$$

$$= 2.2 - 0.85 + 30.95 - 106.76 + 1.22$$

$$= -73.24 \text{ dB}$$

$$d = 1295 \text{ m}$$

The next case is when the interferer is in the backlobe of the subscriber antenna:

$$G_r = -1.6 \text{ dBi}$$

$$G_r\lambda^2/4\pi = -52.15 \text{ dB(m}^2)$$

all other values are unchanged

$$10(\log 1/4\pi d^2) = - G_t - P_t - G_r\lambda^2/4\pi - 106.76 + 1.22$$

$$= 2.2 - 0.85 + 52.15 - 106.76 + 1.22$$

$$= -52.04 \text{ dB}$$

$$d = 113 \text{ m}$$

Table 2 compares the minimum separation distances calculated for the main beam, first sidelobe, and backlobe using the Bellcore modified subscriber antenna pattern and the pattern contained in ITU-R Recommendation 699-2.

Table 2. Minimum Required Separation Distance between Teledesic T1 and CellularVision Subscriber

	Minimum Distance	
LMDS Antenna Orientation	**Using 699-2 Pattern**	**Using Bellcore Pattern**
Main beam	4813 m	4400 m (Table 2-2)
First sidelobe	1295 m	271 m
Backlobe	113 m	40 m (Table 2-2)

The difference in required minimum separation distances, as shown in table 2, is large because of the improved suppression of sidelobes assumed by Bellcore, except in the subscriber antenna mainbeam. Although time did not permit us to perform simulations to determine a value for the modified availability, it is clear that the availability calculated by Bellcore would be significantly degraded.

3.7. SUBSCRIBER-TO-HUB LINK AVAILABILITY

The Bellcore report does not explicitly discuss LMDS subscriber-to-hub availability and proposes no modification of LMDS designs to mitigate the effects of interference; the NRMC concluded that interference on this path is a significant problem. The following analysis determines the FSS station-to-hub distances that must be maintained to avoid degrading availability on the subscriber-to-hub link.

The LMDS hub is to be positioned approximately in the center of an LMDS cell. The LMDS subscribers will be located randomly throughout the LMDS cell and will have their main beams directed at the hub. The strength of the desired receive signal is therefore a function of the subscriber-to-hub distance, with the worst case being a subscriber located in the outer periphery of the cell. The interference signal into the subscriber-to-hub link from FSS uplinks will be harmful when the FSS uplink is within a certain distance from the hub; this distance depends on the azimuth of the FSS antenna relative to the hub.. Therefore, as long as an FSS uplink is not located within this distance, the LMDS subscriber-to-hub link will be unencumbered. For a Teledesic terminal, this distance will have a fixed value since the antenna beam will point over a wide range of azimuths while tracking the Teledesic satellites.

Consider the situation where a Teledesic TST uplink could interfere with the Cellular Vision subscriber-to-hub link. Table 3 lists the values used to compute the minimum TST uplink to CellularVision hub distance.

Table 3. Minimum TST Uplink to CellularVision Hub Distance

	Desired Signal	**Interference**
Cell radius	4.8 km	
Transmit Power	–41.0 dBW	.85 dBW
Tx Power in Rain	-41.0 dBW	17.95 dBW
Tx Antenna Gain	31.0 dBi	36.0 dBi
Signal Bandwidth	.01 MHz	26.5 MHz
Receive Antenna Gain	21.0 dB	21.0 dB
Required C/(N+I)	16.0 dB	

The following procedure yields the minimum separation distance necessary to avoid harmful interference:

The desired received signal from an LMDS subscriber located at the outer range of the cell is:

$$C_{LMDS} = P_t\, G_t\, G_r\, \lambda^2/(4\pi d)^2$$

$$C_{LMDS}\,(\mathrm{dBW}) = P_t(\mathrm{dBW}) + G_t(\mathrm{dB}) + G_r(\mathrm{dB}) + 20\log(\lambda/4\pi) - 20\log(d)$$

$$= -41 + 31 + 21.0 - 61.8 - 20\log(d)$$

$$= -50.8\ \mathrm{dBW} - 20\log(d)$$

$$= -124.4\ \mathrm{dBW}$$

The noise level in the hub receiver is:

$$N\,(\text{dBW}) = 10\log(k) + 10\log(T) + 10\log(B)$$
$$= -228.6\ \text{dBW/(Hz K)} + 27.68\ \text{dB K} + 40\ \text{dB-Hz}$$
$$= -160.9\ \text{dBW}$$

Neglecting the noise term, the maximum allowed interference level is therefore:

$$\text{Interference (dBW)} = -124.4\ \text{dBW} - 16\ \text{dB} = -140.4\ \text{dBW}$$

The minimum distance required is:

$$\text{Interference (dBW)} = .85 + 36 - 38.2 + 21.0 - 61.8 - 34.1 - 20\log(d)$$
$$= -140.4\ \text{dBW}$$
$$= -76.25\ \text{dBW} - 20\log(d)$$
$$d = 1613\ \text{m}$$

The 34.1-dB factor is included to adjust for the difference in the interfering and desired signal bandwidths. The 38.2 dB term is the suppression resulting from the FSS antenna sidelobe.

In a similar fashion, the minimum distance is calculated for heavy rain conditions, allowing for a rain loss of 2.7 dB per km. From the outer limit of the cell, the desired signal at the hub in heavy rain conditions is 13 dB less than that of clear skies. In addition, the TST uplink power is 17.1 dB greater.

$$C_{LMDS} = -137.4\ \text{dBW}$$
$$I = -76.25\ \text{dBW} + 17.1\ \text{dB} - 20\log(d) - .0027d$$
$$= -153.4\ \text{dBW}$$
$$d = 6600\ \text{m}$$

We note that these values are in fair agreement with those of Bellcore (required separation distances for the CellularVision subscriber to hub link of 0.8 km in clear sky and 4.7 km in rain, as given in Table 2-1 in the Bellcore report). Both our calculated separation distances and those of Bellcore substantiate that there is an LMDS availability problem.

In summary, the LMDS hub protection zone against interference from TST uplinks has a radius of 1,613 meters for clear skies, and 6,600 meters for heavy rain conditions. This implies that in order not to affect CellularVision subscribers near the edge of a cell (100% LMDS subscriber-to-hub availability), a TST uplink would have to be located 1,613 meters or more away from the hub under clear conditions (6,600 meters or more from the hub in heavy rain conditions). This is not practical, since it implies that the entire LMDS cell would have to be a protection zone—allowing TST uplinks any closer than this distance would degrade the subscriber-to-hub availability figure. No worthwhile trade between protection zone size and LMDS subscriber to hub availability is possible.

It should be noted in this connection that CellularVision proposes to use the 2-MHz guard bands between video channels for subscriber-to-hub transmissions while the Bellcore spectrum protocol requires that FSS transmissions use these same guard bands as first-priority choices of frequencies.

Clearly, the availability on the subscriber to hub link is insufficient to meet the performance objectives of LMDS operators.

3.8. INTRODUCTION OF ADDITIONAL FSS NETWORKS

The Bellcore study is limited to consideration of LMDS availability in the presence of interference from two FSS networks, namely Teledesic and Spaceway. Additional FSS networks can be expected and, in fact, the FCC has already received an application from Loral Aerospace. Geostationary FSS networks can re-use frequencies when the satellites are separated in orbit by 2 degrees; twelve orbital positions can provide FSS service to the continental United States with elevation angles of at least 20 degrees. Regional FSS networks serving the West coast and East coast markets where population density is high would further increase the potential number of interferers to LMDS subscribers. FSS networks having half-CONUS service areas can be located at longitudes between 55 and 145 degrees west.

Bellcore's consideration of only one FSS network sharing the same frequencies with LMDS gives an incomplete picture of the compatibility of the FSS and the LMDS in common frequency bands (Section 3.5 describes how interference to LMDS subscribers from Spaceway terminals could be substantial). Using the example of the Washington, DC metropolitan area, with Bellcore-modified LMDS parameters and an average of only four Spaceway T1 terminals per CellularVision cell, LMDS availability would be on the order of 98 percent. Using the conservative projection of only ten additional geostationary satellites serving the same geographical area multiplies the number of FSS terminals by six (assuming system parameters identical to those of Spaceway for all 12 networks).

As many as 480 T1 terminals could be transmitting in the Washington, DC, metropolitan area, in contrast to the 80 considered in our earlier example when the only FSS network was

Spaceway. Even if the terminals were uniformly distributed over 27 CellularVision cells, there would be 18 T1s in each and every LMDS cell. Alternatively, if all these terminals were to transmit at the 384-kbps rate, there could be as many as 1920 terminals to consider. In actuality, the FSS terminals would use a mix of transmission rates and the number of terminals in a given area would fall between these extremes.

Figure 3-1 of the Bellcore report provides additional insight into the magnitude of the potential interference; it shows that, in clear sky, five Teledesic T1 terminals in a CellularVision cell will degrade virtually 100 percent of the cell area for 0.5 percent of the time and 15 percent of the cell area for 10 percent of the time. Further, virtually 100 percent of the cell area is degraded for 100 percent of the time in heavy rain. It is clear that 18 Teledesic T1 terminals in and LMDS cell would degrade virtually the entire cell for 100 percent of the time, even in clear weather.

Implementation of additional FSS networks would not be possible even if a way could be found to enable LMDS to coexist with the Teledesic and Spaceway networks.

3.9. ASSESSMENT OF ASSUMPTIONS USED IN THE BELLCORE REPORT

Bellcore concludes its consideration of LMDS availability with a list of what it describes as conservative assumptions used in the analyses. It acknowledges that many propagation factors are difficult to model, but claims that as a result of multiple conservative assumptions, LMDS availability will be much higher than the calculation results would indicate. In the sections that follow, we offer our opinions on the validity of the Bellcore claims.

3.9.1 Relaxation of Performance Criteria

We believe that a reduction of the C/(N+I) objective to 8 to 13 dB (from 26 dB) will result in a degradation of picture quality that is unlikely to be acceptable to subscribers to CellularVision service. Bellcore justifies the reduction by claiming that the reduced levels will be present for only brief periods of time.

We disagree. FSS services to be provided by Teledesic and Spaceway include teleconferencing, telecommuting, videotelephony, basic telephony, data communications, and interactive access to the NII and GII, and will offer these services to both consumer and business subscribers. Many of these users can be expected to require extended periods of service time, for hours at a time in some cases. Therefore, the basis used by Bellcore for reducing the target C/(N+I) (reduced levels present for only brief periods of time) is not valid.

Another problem with the Bellcore approach occurs in Table 1-2, which provides estimates of picture quality as a function of C/(N+I). These estimates are in conflict with test results for QPSK interference on LMDS FM video presented to the NRMC in Document 93. The test results were that, for a C/N ratio of 31 dB and a C/I ratio of 14 dB, a picture quality ranging from marginal to passable resulted (depending on the data rate of the interference and the frequency offset). Bellcore, on the other hand, assumes that a C/(N+I) of 13 dB will produce fine picture quality.

At 8 dB C/I, the test data indicates that picture quality will be marginal to inferior. The data also shows that a C/I of 18 dB produces a passable to fine picture, not a fine to excellent picture as estimated by Bellcore. The test data further show that a C/I of 26 dB is required to produce a fine to excellent picture in the presence of 1.544 mbps QPSK interference, and that a C/I of 26 dB was required to produce at least fine quality regardless of frequency offset between the carrier and the interference.

As is to be expected, the test data show that even higher C/I values are required to produce comparable picture quality when the C/N is reduced from 31 dB to 15 dB.

The reduction of acceptable C/(N+I) ratio to the range of 8 to 13 dB changes LMDS from a noise-limited system to an interference-limited system. LMDS quality would be controlled, not by LMDS system operators, but by external interference not under their control. Contrast this situation with normal practice, where system designers are expected to accommodate interference levels 10 dB below the noise level.

The assumption that C/(N+I) can be reduced from 26 dB to 13 dB is not conservative and can be expected to result in inferior LMDS quality.

3.9.2 Use of Optimistic Subscriber Antenna Pattern

As discussed above, there is great doubt that a consumer product antenna can be consistently maintained in a home or office environment with performance better than the standard contained in the relevant ITU-R Recommendation.

To base improvements in sharing between the LMDS and FSS on the assumption that significant improvements in LMDS subscriber antenna sidelobe performance can be achieved is not conservative.

3.9.3 Neglecting Interference from FSS Terminals Outside an LMDS Cell

Interfering signals will not magically drop to zero at an LMDS cell boundary—neglecting interference sources from adjacent LMDS cells is not a conservative assumption because interference from these sources will degrade the availability of the LMDS systems.

3.9.4 Free Space Propagation

Bellcore claims that the use of free space propagation for their analysis results in conservative statistics for LMDS availability because some interference paths will be blocked by buildings or foliage. However, it is equally true that the same buildings and foliage will block some desired signal paths, and that some interference paths will be enhanced by reflections. Measurements of attenuation due to foliage on desired signal paths at 28 GHz clearly shows that losses can be significant. Reduced desired carrier levels leave less margin for interference, as the test data for picture quality as a function of C/N and C/I show. There will be a differential in foliage loss on some percentage of desired and interference paths where the desired path attenuation is greater than the attenuation on the interference path. In these cases, there will be a degradation of the C/I ratio as well as of the desired signal level.

Use of free space propagation in availability calculations is not conservative.

3.9.5 Frequency of Heavy Rain

Bellcore carried out its calculations by applying the rain rate corresponding to 0.1 percent of the time to the statistics for 1 percent of the time. They claim that actual availability will be 20 percent to 30 percent better than calculated because of this procedure.

LinCom has analyzed the average percentage of an LMDS cell where C/I is less than 13 dB when one Teledesic T1 terminal is located in the cell and rain is considered, and calculated the percentage in two ways. The first method calculated actual attenuation (and increased transmit power) for rain rates corresponding to various percentages of time; the second method calculated the percentage based on the 0.1 percent rain attenuation value being present for 1 percent of the time. The difference in the percent of the LMDS cell area with C/I less than 13 dB was found to be insignificant between the two methods of calculation. It was 0.652 percent when varying rain attenuation as a function of percent of time was applied and 0.69 percent when the 0.1 percent rain rate was assumed for 1 percent of the time.

Calculation of LMDS availability based on application of the 0.1 percent rain rate for 1 percent of the time is therefore not conservative. There is no basis for the claim that actual availability will be 20 percent to 30 percent better than presented in the Bellcore report.

3.9.6 FSS Uplink Antenna

Bellcore claims that actual availability of LMDS will be 10 percent to 15 percent better than calculated because the actual FSS antenna pattern will have peaks and valleys that are always below or equal to the level of the antenna pattern mask. This claim is based on a lack of understanding of the meaning of the antenna pattern mask—in fact, the ITU-R reference antenna pattern recommended for the determination of coordination distance and for the assessment of interference between earth and terrestrial stations is based on the level exceeded by a small percentage of the sidelobe peaks. Thus, there will be nulls in the antenna sidelobe pattern but there will also be peaks that exceed the reference pattern.

Calculation of LMDS availability based on an FSS antenna reference pattern mask is not conservative. There is no basis for the claim that actual availability will be 10 percent to 15 percent better than presented in the Bellcore report.

3.9.7 Satellite Capacity

Bellcore claims that actual availability of LMDS will be 30 percent to 50 percent better than calculated because the satellite loading will almost always be below full capacity (in order to prevent call blocking). However, application of the Erlang B formula to the case of 1,440 Teledesic 16-kbps terminals shows that 1,359 Erlangs of traffic can be provided with 99.9 percent availability. Thus, the percentage of terminals that should be considered active is 94 percent of the maximum capacity, not 60 percent as assumed by Bellcore.

Calculation of LMDS availability based on the full population of FSS transmitters active at the same time is not conservative. There is no basis for the claim that actual availability will be 30 percent to 50 percent better than presented in the Bellcore report.

3.9.8 Interference Spectral Density of Narrowband Interferers

Bellcore claims that actual availability of LMDS will be up to 50 percent better than calculated because their calculations are said to be based on peak interference spectral density rather than on total interference power in the receiver bandwidth. The use of interference spectral density would represent an upper bound on the interference potential.

It is clear that Bellcore used total interference power in their calculations in spite of their statement otherwise (1,440 16-kbps terminals would interfere as if they were T1 terminals if peak interference spectral density were used). LMDS availability when the FSS network consists of 1,440 16-kbps terminals would be much worse than for 15 T1 terminals. The Bellcore results do not show any such effect.

The NRMC final report states that its calculations were based on total power. A check of the program code used for interference calculations verifies the accuracy of this statement.

NASA conducted its simulations of interference caused by 16-kbps Teledesic terminals using both the assumption of peak spectral density and of total power. NASA has found that it can duplicate Bellcore's calculations only if total interference power is assumed[2].

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2 Ibid.

LinCom also has performed simulations for 1,440 16-kbps Teledesic terminals interfering with CellularVision subscribers. LinCom found an average LMDS availability of only 79.93 percent when it performed the calculations on the basis of power spectral density[3].

Bellcore treatment of interference due to narrowband interferers is not conservative, since it is obviously based on total interference power and represents the lower bound on interference potential. Bellcore states that the equivalent interference of a narrowband interferer lies somewhere between the upper and lower bounds and that the lower bound should not be used. Thus, the Bellcore approach was the most optimistic approach—far from being conservative, it underestimated the effect of interference from narrowband interferers.

3.9.9 Aggregate Effect of Bellcore Assumptions on Availability

Bellcore availability calculations do not underestimate LMDS availability. The assumptions that the objective C/(N+I) can be dropped to the range of 8 to 13 dB, and that subscriber antennas can be produced and maintained with significantly better sidelobe performance than recommended by the ITU-R, are, in our opinion, wildly optimistic. The net result will be degradation in LMDS availability. Other factors that Bellcore claims will result in availability 60 percent to 90 percent better than calculated are invalid. The Bellcore approach, far from being conservative, is quite radical and optimistic in nature.

[3] Ibid.

SECTION 4

ANTENNA SYSTEMS

4.1 INTRODUCTION

The Bellcore report calculates link budgets based on a set of antenna masks for the LMDS subscriber receiver and the Teledesic FSS earth station up-link transmitter. Teledesic uses two terminal types: the Teledesic Standard Terminal (TST), which is intended to run at data rates from 16 kb/s up to E1 rates (2.048 Mb/s), and the Teledesic Gigalink Terminal (TGT), which is intended to run at up to OC-24 rates (~1.2 Gb/s).

The first part of this section outlines standards relevant to the evaluation of the LMDS and FSS antenna systems. The second part of this section describes the antenna pattern assumptions made by Bellcore in their study.

The Bellcore study proposes an LMDS antenna that is significantly better than the original submission to the LMDS/FSS 28 GHz Band Negotiated Rulemaking Committee; it also suggests that the Teledesic TST antenna could be significantly improved. These suggested antenna masks are from about 2 to 30 dB more stringent than the current recommendations and performance available from prototype Ka-band antennas. Bellcore did not offer any evidence to indicate that high-performance antennas could be manufactured for consumer use at an affordable price; in addition, Bellcore did not include a margin for the degradation in performance of commercially mass produced antennas operating under adverse weather conditions over extended periods. Since antenna sidelobe levels are often more sensitive than the main-lobe gain to amplitude and phase, maintaining low sidelobes at the antenna end-of-life will increase the cost of the antenna.

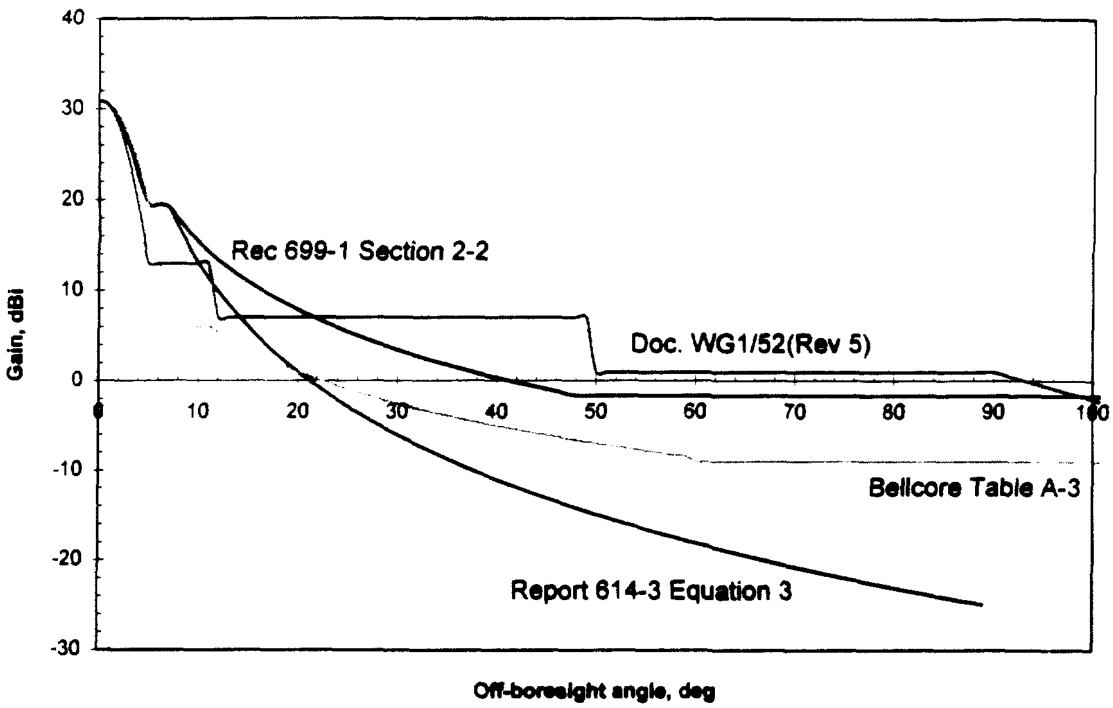
4.2 STANDARDS PERTINENT TO ANTENNA PATTERNS

The following sections describe the standards pertinent to antenna patterns.

4.2.1 LMDS Subscriber Antenna

Recommendation ITU-R 699-2 *(Reference Radiation Patterns for Line-of-sight Radio-relay System Antennas for use in Coordination Studies and Interference Assessment in the Frequency Range from 1 to About 40 GHz)* describes the antenna reference pattern for point-to-point terrestrial radio-relay communication systems. Using Section 3 of the Bellcore report to calculate the antenna size in wavelengths (D/λ) from the stated LMDS main-lobe gain of 31 dBi, the LMDS subscriber antenna has a $D/\lambda = 14.6$. Therefore, the relevant antenna mask is the one for $D/\lambda < 100$ found in Section 2.2 of Rec. ITU 699-2, and reproduced in Figure 1.

Figure 1. LMDS Antenna Masks



The standards present several caveats for the use of this pattern. Rec. ITU-R 699-2 states (in Note 2) that since "the radiation pattern may be worse then the reference radiation pattern" due to effects such as feed system spill over, "the Recommendation should not be interpreted as establishing the maximum limit for radiation patterns...." It further states that it applies only to rotationally symmetric antennas (Note 5). The background study to ITU 699-2, CCIR Report 614-*3 (Reference Radiation Patterns for Radio-relay System Antennas)*, in equation 3 provides an additional pattern for antennas with very low sidelobes such as offset-fed reflectors–Figure 1 reproduces this pattern). The Report further states that the "weather cover" (the radome) may increase the sidelobe levels, and recommends in Section 5 that for frequency sharing problems, backlobe gains should be assumed to be 0 dBi.

4.2.2 FSS Antenna

Section 2 of Recommendation ITU-R S.465-5 *(Reference Earth Station Pattern for use in Coordination and Interference Assessment in the Frequency Range from 2 to About 30 GHz)* recommends an antenna mask for FSS earth stations. It urges caution in applying this pattern to small antennas (that is, where $D/\lambda < 50$), and where spill-over effects may occur. Based on the TST and TGT main-lobe gains of 36 dBi and 50 dBi, respectively, the TST and TGT antenna sizes are $D/\lambda = 26$ and 130. Since the TST $D/\lambda < 50$, the more liberal mask recommended in Note 4 for small antennas prior to 1993 may be more appropriate for use with the TST. Rec. ITU-R S.465-5 also warns "that at large angles, the likelihood of local ground reflections must be considered". Figure 2 shows these two Rec. ITU-R S.465-5 patterns.

CCIR Report 998 *(Performance of Small Earth-Station Antennas for the Fixed Satellite Service)* provides advice on how to minimize antenna sidelobes, recommending the use of RF-absorbing material on structures and reflector edges and the control of factors such as beam taper, blockage, spill-over, and phase errors. Using offset-fed, dual-reflector antennas with conic reflectors (Section 3.2) or shaped reflectors (Section 3.4) resulted in improved antenna masks (see Figure 2).

Recommendation 732 *(Method for Statistical Processing of Earth-Station Antenna Sidelobe Peaks)* allows for averaging the peaks that exceed the recommended mask with the sidelobe regions that do not exceed the mask. According to this recommendation, the antenna sidelobes may exceed the mask for up to 10 percent of the angles within an averaging region. According to Figure 6 of CCIR Report 391-5 *(Radiation Diagrams for Earth Stations in the Fixed Satellite Service for Use in Interference Studies and for the Determination of a Design Objective),* the worst sidelobe peak may exceed the mask by up to about 6 dB.

The commercial experience with phased array antennas is currently limited. CCIR Report 810-3 (*Broadcasting Satellite Service (Sound and Television)* (Reference patterns and technology for transmitting and receiving antennas) suggests that the performance of phased-array antennas can be expected to be similar to the performance of aperture antennas.

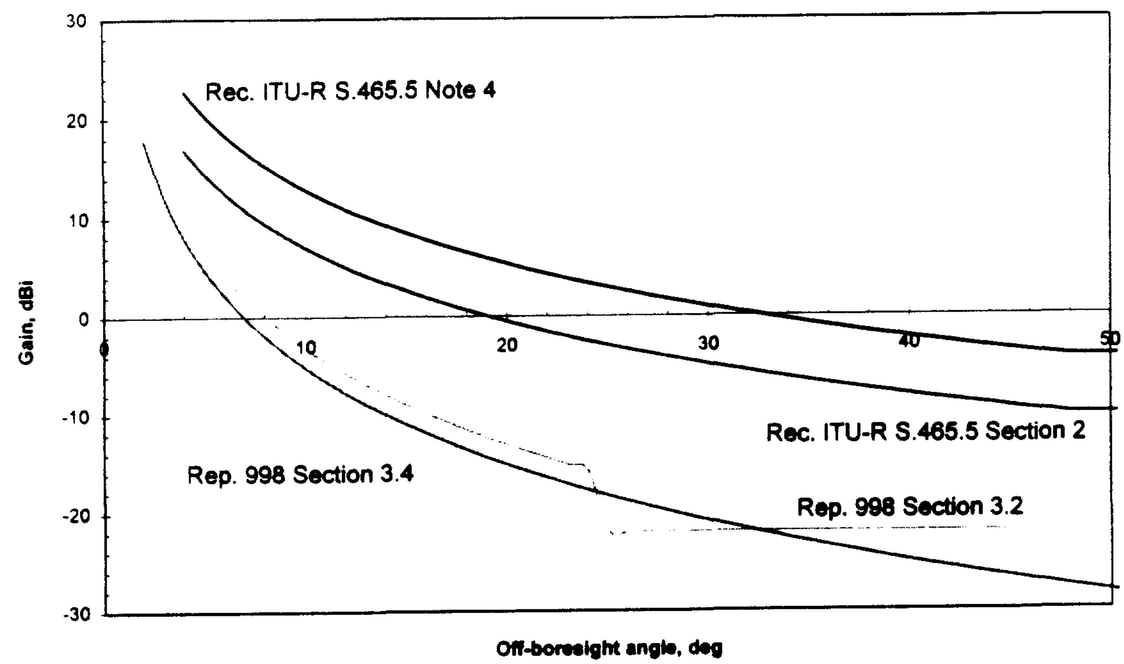
4.3 BELLCORE ASSUMPTIONS FOR FSS AND LMDS SUBSCRIBER ANTENNAS

The following sections describe the assumptions Bellcore made concerning FSS and LMDS subscriber antennas.

4.3.1 LMDS Subscriber Antenna

For the LMDS antenna, Bellcore uses a different antenna mask than was originally proposed to the LMDS/FSS 28 GHz Band Negotiated Rulemaking Committee. This improved pattern, described in Table A-3 of the Bellcore report, has significantly lower sidelobes than the original pattern (see Figure 1). The improved LMDS mask is significantly better than the Recommendation 699-2 mask, and exceeds the Report 614-3 Equation 3 (low sidelobe) mask within ~20° of bore-sight. The Bellcore report presents no LMDS antenna description or pattern measurements to support their antenna mask.

Figure 2. FSS Antenna Masks



4.3.2 Suggested Teledesic Antennas

The Bellcore study assumes that the bore sight of the Teledesic earth terminal will not point to within 40° of the LMDS antenna. This is probably because the Teledesic constellation is designed to ensure that at least one satellite is at least 40° above the horizon. Actual antenna angles could be less than 40° due to differences in LMDS and FSS antenna height due to terrain, ground reflections, or other multipath effects from the Teledesic antenna.

Appendix A of the Bellcore report proposes the following three antenna masks for use with the TST:

An unspecified "ITU pattern" with a sidelobe level 38.2 dB below the main-lobe gain (this is consistent with Rec. ITU-R S.465-5 Note 4 as applied to the TST)

A "Small TST" with a sidelobe level 40 dB down (this is a 1.8-dB improvement over Rec. ITU-R S.465-5 Note 4 as applied to the TST)

A "Typical TST" with a sidelobe level 50 dB down (this is an 11.8-dB improvement over Rec. ITU-R S.465-5 Note 4 or a 6-dB improvement over Rec. ITU-R S.465-5 Section 2 as applied to the TST)

Appendix A also presents the following two patterns for use with the TGT:

An unspecified model of "Andrews Parabolic" with a sidelobe level 58 dB down (this is consistent with Rec. ITU-R S.465-5 Section 2 as applied to the TGT)

An "Andrews SHX Parabolic" with a sidelobe level 68 dB down (this is a 10-dB improvement over the Rec. ITU-R S.465-5 Section 2 recommendation)

Andrews formerly made antennas designated "SHX"; these were horn-reflector antennas, and offered Andrew's best radiation characteristics. "SHX" antennas are no longer manufactured by Andrew; furthermore, horn-reflector antennas are not suitable for use in applications requiring satellite tracking such as the Teledesic system.

In the body of the Bellcore report, five TST antenna sidelobe levels are used to calculate the minimum FSS-LMDS separation data (see Tables 2-1, 2-2, and 2-3 of the Bellcore report). The first three are the patterns suggested for the TST in Appendix A of the Bellcore report and described above; the last two are patterns suggested for the TGT in Appendix A. The TGT terminal has a main-lobe gain of 50 dBi, which is 14 dB greater than the TST main-lobe gain of 36 dBi. (As noted earlier, a sidelobe level 58 dB below the TGT main-lobe gain is consistent with the ITU-R S.465-5 Section 2 recommended level of -8 dBi). Sidelobe levels of 58 dB or 68 dB below the 36 dBi TST main-lobe (as applied in Tables 2-1, 2-2, and 2-3) represent actual antenna sidelobe gains of -22 dBi and -32 dBi, respectively. This is difficult, if not impossible, to realize in a consumer-affordable antenna the size of the TST antenna.

In Section 3.5.3, the Bellcore study states that the FSS antenna masks represent an absolute upper limit on the sidelobes and feed spill-over of the FSS antenna. This is not consistent with the statistical averaging of sidelobes allowed in Recommendation 732 or Report 391-5.

4.4 ANTENNA PERFORMANCE

The following paragraphs contain descriptions of theoretical and measured antenna patterns, and compare patterns with recommended antenna masks. The performance of actual, commercially mass-produced antennas operating under adverse weather conditions over extended periods with little or no maintenance is likely to be inferior to the performance obtained for antennas described here.

Sidelobe mitigation techniques for aperture antennas include offset feeds and multiple, shaped reflectors to reduce blockage and otherwise control the aperture illumination function. Sidelobe mitigation techniques for phased arrays include array element amplitude and phase control. Aside from the additional non-recurring costs associated with designing these higher performance systems, recurring costs increase due to the increase in parts count (e.g., for aperture antennas - the sub-reflector, its supporting structure and de-icing heaters; for array antennas - element gain control and finer quantization of phase shifters). Beam taper used to decrease sidelobe levels will also reduce the effective aperture size and, consequently, main-lobe gain. This must be compensated either by increasing the physical antenna size, or increasing the transmitter power and decreasing the effective noise temperature of the receiver.

Any of these solutions will increase the cost of the subscriber equipment. In addition, since antenna sidelobe levels are often more sensitive than the main-lobe gain to amplitude and phase errors caused by manufacturing tolerances or environmental effects, maintaining low sidelobes at the antenna end-of-life will increase the cost of the antenna.

4.4.1 Commercial USAT Aperture Antennas

K_a-band USAT antennas are not commonly commercially available; however, Ku-band USAT antennas are. The Prodelin 60 cm ($D/\lambda \sim 24$) antenna, which is used as the basis of the ACTS USAT antenna, appears to meet the ITU-R S465-5 Section 2 mask, but does not meet the "Typical TST" improvement suggested by Bellcore.

4.4.2 Experimental K_a-Band U/VSAT Aperture Antennas

The ACTS USAT antenna is a small ($D/\lambda = 36$) antenna similar in size to the TST antenna. The USAT antenna is a single-reflector, offset-fed parabola that meets the ITU-R S465-5 Note 4 mask, but does not meet the "Typical TST" improvement suggested by Bellcore.

The ACTS LBR-2 VSAT antennas ($D/\lambda = 120$ and 240) are similar in size to the TGT antenna. The LBR-2 antennas are single-reflector, offset-fed parabolas that meet the ITU-R S465-5 Section 2 mask, but do not meet the "Typical TST" improvement suggested by Bellcore.

4.4.3 Phased-Array Antennas

K. Imai describes an experimental Ku-band electronically steerable phased-array antenna in *Digital SNG RF Terminal Using Flat Antenna, AIAA-94-1066-CP, 15th AIAA International Communications Satellite Systems Conference*. This antenna is a 60-cm-by-60-cm (~30 λ by 30 λ) square. Along the diagonal of the square, the antenna meets the ITU-R

S465-5 Section 2 mask, but does not meet the "Typical TST" improvement suggested by Bellcore.

Appendix A describes the simulation of a 29-GHz phased array antenna similar in gain to the requirements for the TST. The simulation results indicate that the antenna meets the ITU-R S465-5 Note 4 mask, but may not meet the "Typical TST" improvement suggested by Bellcore.

SECTION 5

PROPOSED BELLCORE PROTOCOL

The Bellcore report provides the outline of a proposed protocol as it would apply to a specific LMDS provider and two FSS providers. The Bellcore report also discusses a second LMDS system, but in even less detail. Even for this limited set of providers, the Bellcore report does not provide a complete description of the protocol and contains a number of technical flaws. For example, the Bellcore report provides availability results only for the case of one LMDS provider subject to the transmission of one FSS provider.

There are several fundamental issues related to such a protocol. These concerns are the following:

- The protocol is incompatible with satellite technology and system design
- The protocol addresses one or two specific LMDS systems and FSS systems in isolation, rather than the more realistic situation of multiple systems
- The protocol largely ignores the details and significant problems in the technical implementation and operation of the protocol
- The protocol ignores the administrative issues and problems associated with implementation
- The protocol will significantly limit the possibilities for efficient use of the spectrum by the FSS

The following sections discuss these issues.

5.1 INCOMPATIBILITY WITH SATELLITE TECHNOLOGY AND SYSTEM DESIGN

Satellite design requires that users of low to medium bandwidth (that is, up to several megahertz each) be contiguous. In traditional satellite transponder technology (where uplinks are down-converted and amplified for the downlink), each transponder generally covers from 40 MHz up to several hundred megahertz. This design places many users of smaller bandwidth contiguously within the transponder bandwidth so they can be amplified together for transmission on the downlink.

On-board processing to replace transponder technology has become available over the past decade, making service possible to a smaller and more affordable class of terminal. This has effectively opened entirely new market areas, such as FSS in the 27.5 to 29.5 GHz bands of interest. The system can perform on-board demodulation either with surface acoustic wave (SAW) devices or with digital processing based on space-qualified electronics. The SAW implementation Fourier-transforms the entire bandwidth of many users as an analog operation, and then digitally interprets the results. Digital implementations convert the entire bandwidth of many contiguous users from analog to digital form and then transform it as a unit, using signal processing techniques to minimize the power and weight required. In both cases, implementation within the weight and power limitations of spacecraft payloads becomes feasible only if the system can process the bandwidth in blocks of many contiguous users.

Traditional transponders and newer on-board processing techniques both require contiguous bandwidth for users. A protocol that selectively places users in scattered gaps is therefore incompatible.

5.2 ISOLATED CASES

The Bellcore protocol focuses only on one or two LMDS and FSS systems. Furthermore, it treats a combination of one LMDS system and one FSS system as an isolated pair. A candidate protocol for a given LMDS system should address multiple FSS systems that operate simultaneously; it should not be limited to Teledesic and Spaceway. Additionally, for a set of protocols to be considered a comprehensive solution, it should address all FSS systems for each LMDS system. Finally, the various LMDS protocols imposed on each FSS system must be checked for compatibility. More specifically, terminals within a given FSS system will be operating in different geographical locations and can be subject to different protocols. Each of the differing LMDS protocols must be shown to be consistent with the protocols and operation required for the satellite. There is no evidence to indicate that a credible and comprehensive set of protocols for the various LMDS systems can be constructed without raising the level of complexity for each FSS system to unmanageable levels.

5.3 TECHNICAL ISSUES OF IMPLEMENTATION AND OPERATION

The Bellcore report discusses the protocol as a concept, but treats inadequately or ignores altogether the technical aspects of implementation and operation. In fact, satellite system control becomes far more complex and costly than currently planned for proposed FSS systems. This issue prevails even if we suspend concern over the fundamental problem expressed in section 5.1 that the proposed protocols are incompatible with satellite operation.

For example, the proposed protocol could require satellite terminal location to be known with significantly more accuracy than would otherwise be required by the FSS systems, imposing a greater burden on FSS earth terminals. Furthermore, the control system for the